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Corrigendum

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The publisher advises that the second author's name is incorrect and should be Josie Carwardine.

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Review

The threats to Australia's imperilled species and implications for a national conservation response

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Abstract. Since European occupation of Australia, human activities have caused the dramatic decline and sometimes extinction of many of the continent's unique species. Here we provide a comprehensive review of threats to species listed as threatened under Australia's *Environment Protection and Biodiversity Conservation Act 1999*. Following accepted global categories of threat, we find that invasive species affect the largest number of listed species (1257 species, or 82% of all threatened species); ecosystem modifications (e.g. fire) (74% of listed species) and agricultural activity (57%) are also important. The ranking of threats was largely consistent across taxonomic groups and the degree of species' endangerment. These results were significantly different ($P < 0.01$) from recent analyses of threats to threatened species globally, which highlighted overexploitation, agriculture and urban development as major causes of decline. Australia is distinct not only in the biodiversity it contains but also in the extent and mixture of processes that threaten the survival of these species. Notably, the IUCN threat classification scheme separates the numerous threats (e.g. urban development, agriculture, mining) that cause habitat loss, fragmentation and degradation, hence further research is required to quantify the net impact of these types of habitat change. We provide feasible suggestions for a more coordinated national approach to threatened species conservation, which could provide decision makers and managers at all levels with improved resources and information on threats and management. Adequate policy, legislative support and funding are critical for ensuring that on-ground management is successful in halting the decline of Australia's threatened species.

Additional keywords: EPBC Act, extinction, fire, habitat loss, invasive species, protected areas, threatening processes

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Introduction

Australia accounts for 5% of the world's landmass, but supports 12.5% of chordate species, and almost 8% of all described plant, animal and fungal species (Chapman 2009). Most of these species occur nowhere else on earth, with >85% of Australia's plants, mammals, reptiles and amphibians being endemic (Chapman 2009). Australia is one of 17 'megadiverse' nations (Mittermeier *et al.* 1997), and one of only two of these nations that is also wealthy in economic terms (the other being the United States: World Bank 2017). Human population density is

comparatively low and geographically biased to the country's south-east coastal areas (ABS 2016). Additionally, while deforestation and intensive land-uses have impacted much of south-western and eastern Australia (Bradshaw 2012; ABARES 2016), vast areas of the continent have experienced low human impact and are considered largely intact (Watson *et al.* 2016). These factors indicate that Australia has the potential to conserve its remaining species.

However, this objective contrasts with Australia's extremely poor record of species' extinctions globally (IUCN 2015*a*, 2015*b*). Since European occupation, 90 extinctions of Australian taxa have been recognised under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) (36 plants, 27 mammals, 22 birds, four frogs and one invertebrate: Commonwealth of Australia 2015*a*). The actual number of extinctions is higher, as many known extinctions are yet to be listed under national legislation (e.g. *Tornelasmias capricorni*: Ponder 1996); *Fluvidona dulvertonensis*: Mollusc Specialist Group 1996), and many extinctions are likely to have gone unrecorded (Tedesco *et al.* 2014). While many of Australia's best known extinctions (e.g. thylacine (*Thylacinus cynocephalus*), pig-footed bandicoot (*Chaeropus ecaudatus*), paradise parrot (*Psephotellus pulcherrimus*)) occurred decades ago, the extinction rate remains unabated for some taxonomic groups (Woinarski *et al.* 2015). At least three extinctions have occurred since 2009 (Christmas Island pipistrelle (*Pipistrellus murrayi*), Christmas Island forest skink (*Emoia nativitatis*) and Bramble Cay melomys (*Melomys rubicola*)), and many Critically Endangered species are declining (Garnett *et al.* 2011; Woinarski *et al.* 2014), showing that Australia's biodiversity crisis is ongoing (Woinarski *et al.* 2017*a*). Without significant improvements in our efforts, it is estimated that a further 17 threatened birds and mammals are likely to be lost from Australia over the next 20 years (Geyle *et al.* 2018). As a signatory of the Convention on Biological Diversity, Australia has international obligations to prevent these and any other extinctions. Specifically, Aichi Target 12 of the United Nation's Strategic Plan for Biodiversity 2011–2020 calls for the prevention of the extinction of known threatened species (CBD 2010).

A recent review of the threats to imperilled species globally highlighted that overexploitation (e.g. hunting, logging), agriculture and urban development are currently the leading drivers of species decline (Maxwell *et al.* 2016). Given Australia's unusual biophysical circumstances of geographic isolation combined with a long history of fire (Crisp *et al.* 2011), it is likely that the dominant threats interact with Australian biodiversity in unique ways. Following the release of Australia's first Threatened Species Strategy in 2015 (Commonwealth of Australia 2015*b*), it is timely to provide a comprehensive review of the threats that imperil threatened species across Australia, as this information is critical to successful, long-term conservation action.

This review complements previous assessments of threat incidence among particular taxonomic groups (Burgman *et al.* 2007; Garnett *et al.* 2011; Woinarski *et al.* 2015; Allek *et al.* 2018). We focus on the 1533 freshwater and terrestrial invertebrate, vertebrate and plant species and subspecies (hereafter, taxa) listed as threatened (Vulnerable, Endangered or Critically Endangered) under Australia's EPBC Act.

The threats to the listed taxa are documented in the Australian Government's Species Profiles and Threats Database (SPRAT Database: Commonwealth of Australia 2015*a*), although in many cases this documentation is conjectural or based on limited evidence, and often does not discriminate between primary causal factors and factors that may have contributed in a minor way to decline. This is not necessarily a failing of the database, but reflects the lack of knowledge of the threats affecting some Australian taxa. For many taxa, such as birds, the SPRAT database draws on the same data used for the IUCN assessments, so that the two sets of threat data should be broadly comparable. Here, threats are categorised using the IUCN Red List classification, which describes the proximate threats to species (Salafsky *et al.* 2008; IUCN 2017). Table 1 provides a description of the threat categories used.

A primary objective of our analyses is to compare the relative frequency with which threatening processes are listed under Australia's threatened species legislation. In doing so, we provide a national-level understanding of which threats are thought to be affecting Australia's threatened taxa. We then consider current efforts to address the threats to Australian biodiversity, including the national Threatened Species Strategy. We conclude by providing recommendations for enhancing the planning and governance environment of threat management to improve the conservation of Australian biodiversity. The methods for data compilation and analysis are detailed in the Supplementary Material (available online).

Prevalence of threats to Australian threatened taxa

Invasive species, ecosystem modifications and agriculture are the threats listed as affecting the largest numbers of Australian threatened taxa (Fig. 1). This pattern was consistent across each broad taxonomic group (plants, invertebrates and vertebrates) (Fig. 2), category of endangerment (Vulnerable, Endangered and Critically Endangered) (Fig. 2), and across all vertebrate classes other than fish (for which invasive species, ecosystem modifications and pollution are the most common threats) (Fig. 2). Using a Kruskal–Wallis test, we found no statistically significant difference among groups in the relative rankings of broad threat categories (broad taxonomic groups ($H = 0.028$, $P = 0.98$), vertebrate groups ($H = 2.59$, $P = 0.63$) and category of endangerment ($H = 0.24$, $P = 0.88$)).

Invasive species is the most common threat, listed as affecting 82% ($n = 1257$) of threatened taxa in Australia (Fig. 2). In total, 267 invasive species (207 plants, 57 animals, 3 pathogens) are listed as affecting Australian threatened taxa. The European rabbit (*Oryctolagus cuniculus*) threatens 21% ($n = 322$) of EPBC Act–listed taxa (Fig. 3). The impacts of rabbits on Australian taxa are numerous and include: direct herbivory, particularly of seedlings and saplings (Denham and Auld 2004); competition for food resources (Bird *et al.* 2012); land degradation (Eldridge *et al.* 2006); and facilitating hyperpredation (Smith and Quin 1996). One species that has experienced considerable impacts from rabbits is the purple wood wattle (*Acacia carneorum*, Vulnerable), which occurs in the south-east of central Australia (DEWHA 2008*a*). Rabbit grazing is particularly pronounced on the seedlings of this species, which has

Table 1. The threat categories used in this analysis and their description

IUCN Red List threat category	Abbreviated threat category	Description
Residential and commercial development	Urban development	Threats from human settlements or other non-agricultural land uses with a substantial footprint
Agriculture and aquaculture	Agriculture	Threats from farming and ranching as a result of agricultural expansion and intensification, including silviculture, mariculture and aquaculture
Energy production and mining	Energy production	Threats from production of non-biological resources.
Transportation and service corridors	Transportation	Threats from long narrow transport corridors and the vehicles that use them.
Biological resource use	Overharvesting	Threats from consumptive use of 'wild' biological resources including both deliberate and unintentional harvesting effects; also persecution or control of specific species.
Human intrusion and disturbance	Human disturbance	Threats from human activities that alter, destroy and disturb habitats and species associated with non-consumptive uses of biological resources.
Natural system modifications	Ecosystem modifications	Threats from actions that convert or degrade habitat in service of 'managing' natural or seminatural systems, often to improve human welfare. For example, fire and fire suppression; dams and water use.
Invasive and other problematic species, genes and diseases	Invasive species	Threats from non-native and native plants, animals, pathogens/microbes, or genetic material that have or are predicted to have harmful effects on biodiversity following their introduction, spread and/or increase in abundance.
Pollution	Pollution	Threats from introduction of exotic and/or excess materials or energy from point and non-point sources.
Geological events	Geological events	Threats from catastrophic geological events.
Climate change and severe weather	Climate change	Threats from long-term climatic changes that may be linked to global warming and other severe climatic/weather events that are outside of the natural range of variation or potentially can wipe out vulnerable species habitat.

caused a serious lack of recruitment, impacting the species' regeneration and hence viability (Auld 1993).

Four other invasive species (feral goat (*Capra hircus*), feral cat (*Felis catus)*, feral pig (*Sus scrofa*) and root rot fungus (*Phytophthora cinnamomi*)) are listed as threatening over 100 threatened taxa each (Fig. 3). The purple copper butterfly (*Paralucia spinifera*, Vulnerable), for example, is threatened by feral pigs, feral goats and several invasive plant species (e.g. blackberry (*Rubus fruticosus*) and scotch broom (*Cytisus scoparius*)), all of which contribute to the degradation of the species' habitat (TSSC 2016*a*). The threat from *Phytophthora cinnamomi*, a soil-borne water mould pathogen that destroys the roots of affected plants, is well documented (Shearer *et al.* 2007; Cahill *et al.* 2008), particularly in the Eastern Stirling Range Montane Heath Community in Western Australia, where numerous endemic taxa are threatened with extinction (Barrett and Yates 2015). Phytophthora has also been documented in forests and heathlands of Victoria (Weste 2003; Reiter *et al.* 2004), New South Wales (McDougall *et al.* 2003) and Tasmania (Podger *et al.* 1990).

Feral cats and the European red fox (*Vulpes vulpes*) are two invasive species that have had, and continue to have, a devastating impact on Australian species, particularly critical-weight-range mammals (Woinarski *et al.* 2015). The feral cat and the European red fox are known to threaten 123 and 95 EPBC Act–listed species, respectively. One of these species is the greater stick-nest rat (*Leporillus conditor*, Vulnerable). Feral cats and foxes have had a catastrophic impact on the greater stick-nest rat over much of its range and the species now persists only in fenced reserves and cat- and fox-free islands (Legge *et al.* in press). The other species in the genus, the lesser stick-nest rat (*Leporillus apicalis*, Extinct) is extinct, almost certainly because of predation pressure from feral cats and foxes across the entirety of its range (Woinarski *et al.* 2014).

Problematic native species are listed as threats for one-fifth of threatened taxa. The most prevalent is grazing pressure from macropods, which is listed as a threat to 152 threatened plant and five threatened animal taxa. Increased macropod abundance in some regions (e.g. Barker and Caughley 1991; Silcock *et al.* 2013) is partly due to lethal control and exclusion of dingoes (*Canis dingo/familiaris*) (Letnic *et al.* 2012), the proliferation of reliable water points (Fensham and Fairfax 2008) and greater extent and reliability of palatable feed grasses (Newsome 1975).

Ecosystem modification, which includes the impacts of changed fire and hydrological regimes, is listed as a threat for almost three-quarters of threatened taxa (74%, $n = 1136$). Fire has had a considerable influence on species and ecosystems across much of the continent and many species have evolved to cope with or rely on particular fire regimes (Woinarski and Recher 1997; Bowman *et al.* 2012). Since European occupation, many areas have experienced dramatic changes in fire regime, ranging from reductions in the incidence of fire to increases in the frequency, extent and intensity of fire (Russell-Smith 2001; Ward *et al.* 2001). Numerous plant species require fire to germinate, or to open up intertussock spaces for recruitment, and are declining due to reductions in fire frequency (Stuwe and Parsons 1977; Morgan 1998; Williams *et al.* 2006). For example, the orange dryandra (*Banksia aurantia*, Critically Endangered), known to occur only within Wandoo National Park in Western Australia, is threatened by a lack of fire (DEWHA 2008*b*). The species requires a specific fire regime for it to regenerate successfully and one population of the species is likely to have already gone extinct due to lack of fire (TSSC 2013).

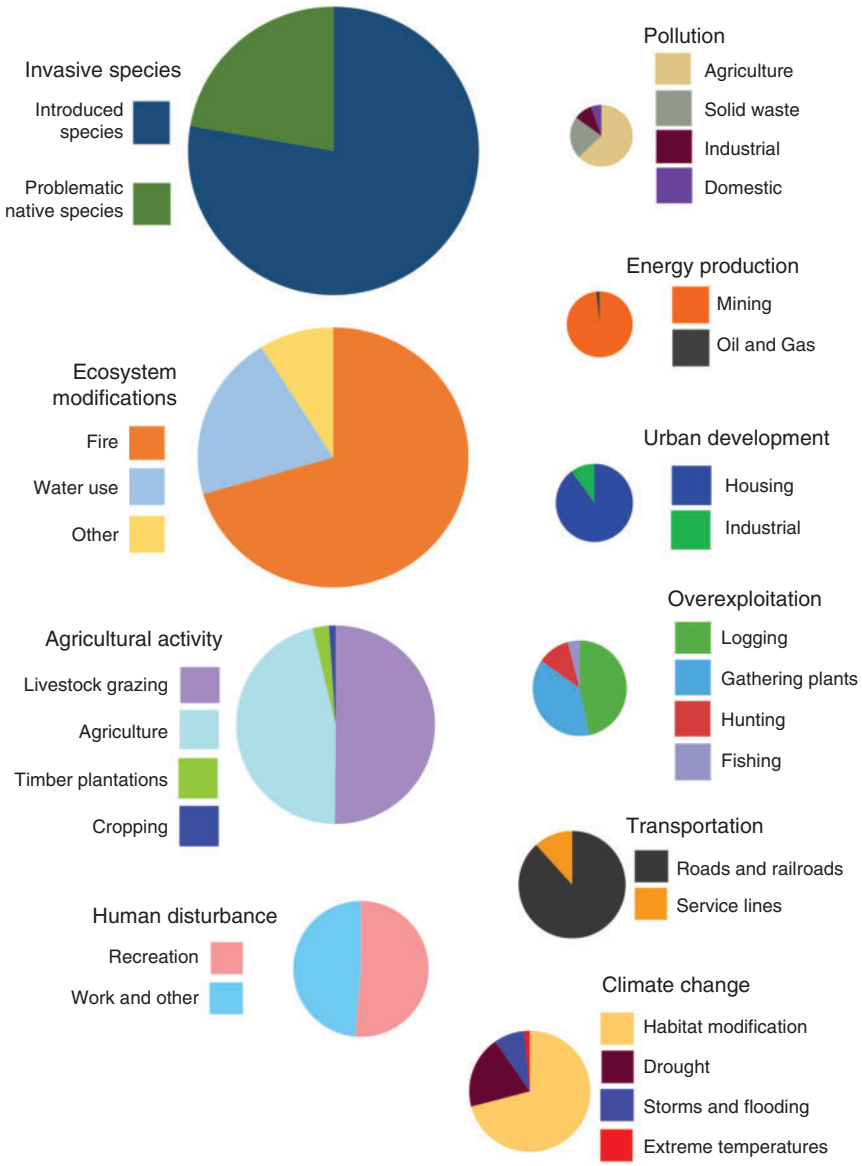

Fig. 1. The prevalence of threats to Australian threatened taxa ($n = 1533$). Each chart is scaled according to the number of EPBC Act–listed taxa listed as being affected by each threat category (e.g. Urban development). Each pie chart segment represents a subclass threat (e.g. Housing). We removed threat categories that impacted <20 taxa (e.g. Geological events) and subclass threats that impact <5 taxa (e.g. Renewable energy) as they were too small to be displayed effectively. See Table S3 available as supplementary material for further details.

Across much of Australia, hydrological regimes have changed substantially since the 1800s, through water impoundment (Kingsford 2000), drawdown of aquifers (Powell *et al.* 2015), drainage of swamps (Bickford *et al.* 2008; Casanova and Powling 2014) and salinity (National Land and Water Resources Audit 2001). There are over 500 large dams (volume >1 GL) and many thousands of smaller dams across Australia (ABS 2010), which together have had a significant impact on biodiversity, particularly on freshwater species and those that occur in agricultural landscapes (Kingsford *et al.* 2017). The silver perch (*Bidyanus bidyanus*, Critically Endangered), for example, is heavily impacted by water management and use, in addition to a multitude of other threats (e.g. invasive species, invasive pathogens: DoE 2013). The species is endemic to the Murray–Darling Basin, which has an estimated 4000 barriers to fish movement (Lintermans 2007). These dams, weirs and other structures severely impact this migratory freshwater species (DoE 2013).

Agricultural activity (e.g. cropping, livestock grazing and wood plantations) is the third most commonly listed threat, affecting 57% of taxa ($n = 873$) (Fig. 1). The Margaret River burrowing crayfish (*Engaewa pseudoreducta*, Critically Endangered), for example, is threatened by several activities

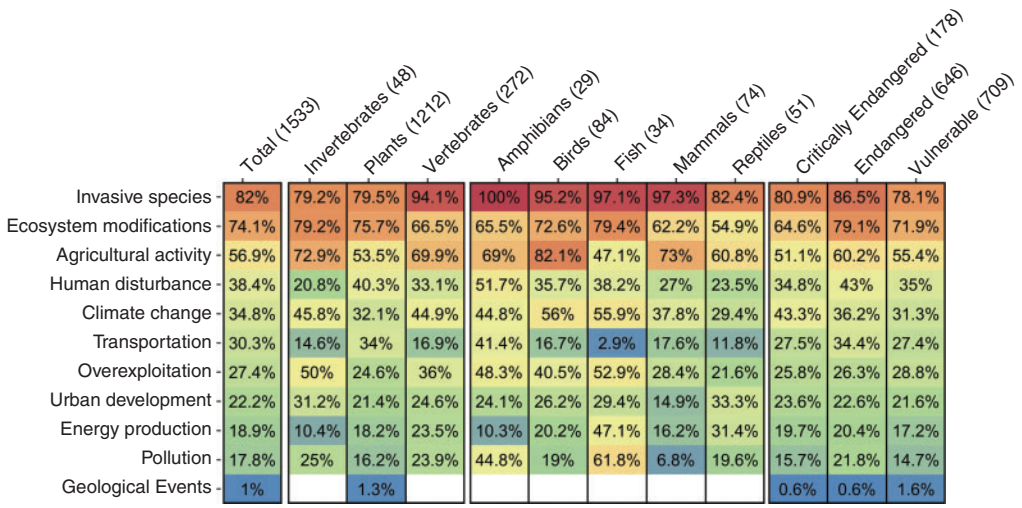

Fig. 2. The prevalence of threats to Australian threatened taxa across broad taxonomic groups, vertebrate taxonomic groups and extinction risk categories. The colour of each cell is scaled to correspond with the percentage of the species group listed as being affected by each threat category. For example, cells that represent species groups for which 100% are affected by a particular threat category (e.g. amphibians by invasive species) are shaded red. Cells that represent groups of which only a small percentage are threatened (e.g. plants by geological events) are shaded blue. Cells representing groups that have no species listed as being affected by a particular threat are left blank (e.g. vertebrates by geological events).

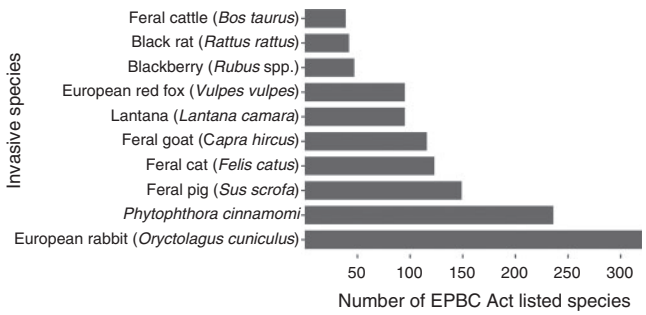

Fig. 3. The 10 invasive species listed as impacting the greatest number of EPBC Act–listed threatened taxa ($n = 1533$). In total, 267 invasive species are listed as impacting EPBC Act–listed species: 207 plants, 57 animals and three pathogens. This includes 230 non-native species (187 plants, 41 animals and two pathogens) and 37 problematic native species (20 animals, 16 plants and one pathogen).

associated with agriculture, such as land clearing and cattle grazing that have degraded and destroyed much of the species' habitat (DEWHA 2009). Livestock grazing is the dominant land use in Australia, occupying 54% of the continent (ABARES 2016) and threatening 621 taxa.

Human disturbance, originating from recreational, military, and other outdoor activities is listed as a threat to 588 taxa. Human disturbance is one of the key threats to the eastern subspecies of the hooded plover (*Thinornis rubricollis rubricollis*, Vulnerable). Recreational activities such as beach driving and dog-walking both contribute to crushing of eggs and chicks and disturbance of nesting birds (Dowling and Weston 1999; Garnett *et al.* 2011).

The impacts of climate change and severe weather, particularly the alteration of species' habitat due to changes in temperature and rainfall, drought, temperature extremes, and storms and flooding, are listed as threatening 533 Australian taxa. The impacts of climate change are anticipated as major future threats (e.g. habitat shifting in response to changed precipitation and temperature regimes: Garnett *et al.* 2013; Reside *et al.* 2013), but numerous species are already being affected. Carnaby's black-cockatoo (*Calyptorhynchus latirostris*, Endangered) and the grey-headed flying-fox (*Pteropus poliocephalus*, Vulnerable), for example, suffer high rates of mortality in periods of extreme heat (Welbergen *et al.* 2008; Saunders *et al.* 2011). Additionally, it is likely that the number of taxa that will be, or are already, impacted by climate change is greater than reported here, as it is only included as a threat when there is existing evidence of a direct impact (TSSC 2015*a*). Additionally, the interaction between climate change and other threats is not likely to be captured in the SPRAT databases. The impacts of climate change are likely to be highly interactive, altering the severity and extent of other threats such as fire (Hughes 2003), water use (Nielsen and Brock 2009) and agriculture (Hannah *et al.* 2013).

Numerous forms of transport corridors and lineal infrastructure, such as roads, railroads, and utility and service corridors, threaten 465 taxa. Roads predominantly cause direct mortality from vehicle collisions and inhibit dispersal, which can severely affect population genetics (Taylor and Goldingay 2010). Because roadside verges now represent the only or main remaining native vegetation in many largely cleared regions, plant species, such as the Scott River boronia (*Boronia exilis*, Endangered), are particularly susceptible to road construction and maintenance (Trombulak and Frissell 2000). This small flowering plant endemic to south-western Australia is threatened by road maintenance activities, which include the construction of drainage channels, mowing, and other related disturbances (TSSC 2016*b*).

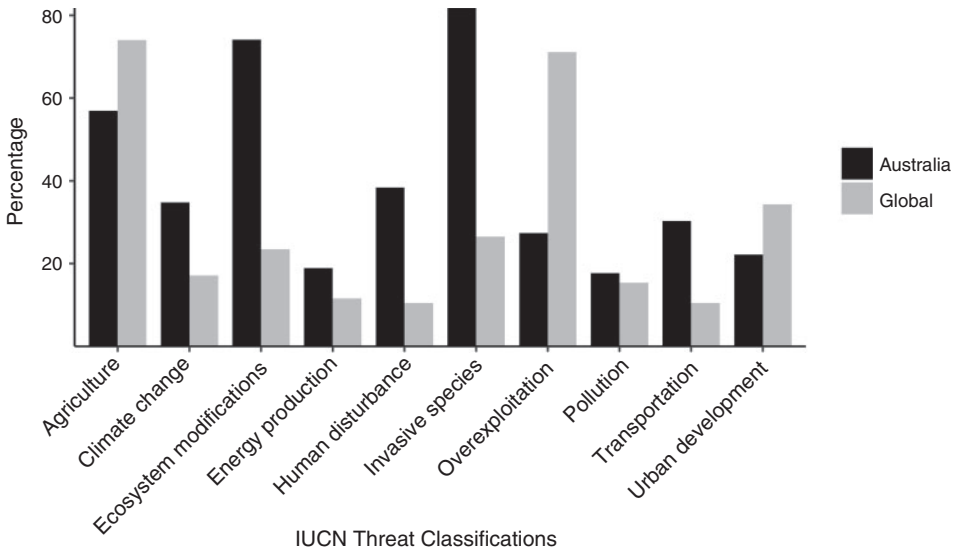

Fig. 4. The percentage of Australian ($n = 1533$) and global ($n = 5296$) threatened species threatened by each threat category. Information on the threats to global species was taken from data used by Maxwell *et al.* (2016), who evaluated the threats to 8688 terrestrial, freshwater and marine species listed as Near Threatened, Vulnerable, Endangered or Critically Endangered on the IUCN Red List of Threatened Species. To enable a direct comparison with the threats to EPBC Act–listed taxa, we removed Near Threatened species and species groups comprising marine and mostly marine species from the database of Maxwell *et al.* (2016).

Overexploitation – including the harvesting of species from the wild (e.g. hunting, fishing, collection, logging) – is affecting 420 taxa. The giant barred frog (*Mixophyes iterates*, Endangered) is one species threatened by overexploitation, specifically logging, as the species is particularly sensitive to its impacts (Lemckert 1999). However, it is important to note that chytrid fungus likely played a major role in the decline of the species in the past few decades (Mahony 1993), as with many Australian amphibians (DSEWPC 2013). The impacts of threats such as logging are now having an increased impact on species that are already under pressure (Lemckert and Brassil 2000).

Urban development, including housing, commercial, industrial, tourism and recreational development, is listed as a threat to 341 taxa. Caley's grevillea (*Grevillea caleyi*, Endangered) is one such species and has lost 85% of its habitat due to clearing for urban growth around Sydney, New South Wales (Auld and Scott 1997). Although one population of the species is protected within a national park, other populations are considered highly disturbed (Auld and Scott 1997) and are at risk from further fragmentation (DEC 2004).

Energy production, which includes the exploration, development and production of fossil fuels, renewable energy and minerals, threatens 289 Australian threatened taxa. Abbott's booby (*Papasula abbotti*, Endangered) and Christmas Island frigatebird (*Fregata andrewsi*, Endangered) have both experienced a substantial reduction in habitat due to mining operations on Christmas Island (TSSC 2015*b*, 2016*c*). Phosphate mining on Christmas Island has substantially reduced the area and quality of nesting habitat, causing population declines of both species (TSSC 2015*b*, 2016*c*).

Pollution, from urban wastewater, industrial and agricultural effluents and solid waste, is threatening 225 Australian taxa. The threat from pollution is particularly high for freshwater species (Dudgeon *et al.* 2006). The habitat of the Blue Mountains water skink (*Eulamprus leuraensis*, Endangered), a lizard endemic to New South Wales, is currently under threat from numerous forms of pollution (TSSC 2016*d*). Runoff from roads and industrial sites, inappropriate dumping of industrial and domestic waste, and pesticide, herbicide and fertiliser runoff from forestry and agriculture are all believed to be impacting the species (TSSC 2016*d*).

Comparison of threats between Australian and globally threatened species

In their recent threat assessment of IUCN Red List Threatened and Near Threatened terrestrial, freshwater and marine species ($n = 8688$), Maxwell *et al.* (2016) showed that overexploitation (71.8%), agriculture (62.2%) and urban development (34.7%) (Fig. 4) are the dominant threats to species globally. We used the data provided in their assessment to compare threats to species globally with those affecting species in Australia (we removed Near Threatened species and species groups comprising marine and mostly marine species to enable direct comparison with the threats to the EPBC Act–listed taxa used in our analysis). Of the 5296 IUCN Red Listed species examined, agriculture (74.0%), overexploitation (71.1%) and urban development (34.3%) are the most commonly listed threats to these species. Here, we found that invasive species, system modifications and agriculture are the most prevalent threats to threatened taxa in Australia. The relative proportional incidence of the threats to Australian species differs significantly from those affecting species globally ($\chi^2 = 97.9$, d.f. $= 9$, $P < 0.0001$) (Fig. 4).

Invasive species and system modifications are more prevalent in Australia, and overexploitation more prevalent globally. Australia's long separation from other continents and its fauna and flora's subsequent evolution in isolation has likely had a considerable influence on these species' susceptibility to the impact of invasive species (Blumstein 2002; Cox and Lima 2006). Additional to this is the interaction between invasive species and the boom–bust ecological cycles driven by climate that characterises much of the continent. Climate phenomena such as the El Niño Southern Oscillation have been found to influence the interactions between introduced predators and native mammals, in many cases increasing predation pressure on species already under stress (Letnic *et al.* 2005; Letnic and Dickman 2006).

Ecosystem modifications, particularly changed fire regimes, are also more frequently noted threats to threatened species in Australia than globally. Since European occupation, the changes to fire regimes in Australia have been complex (Bowman 2003). These changes vary considerably: from ecosystems that evolved with no fire now experiencing devastating fires (e.g. Tasmanian high-altitude relict forest: Marris 2016), ecosystems that evolved with fire now experiencing very little fire (e.g. some areas of Cape York grassy woodlands: Crowley and Garnett 1998), through to areas that evolved to a particular fire regime experiencing a new regime that does not meet the ecological needs of the species (e.g. Sydney bushland: Auld and Scott 1997).

In contrast, overexploitation threatens a higher proportion of species globally than in Australia. The impact of overexploitation is particularly pronounced in the tropics (Bradshaw *et al.* 2009), with logging (Barlow *et al.* 2006), bushmeat hunting (Ripple *et al.* 2016), overfishing (Dudgeon *et al.* 2006) and the pet trade (Harris *et al.* 2017) all having a considerable impact on species globally. However, it is important to note that overexploitation has had, and continues to have, a devastating impact on some Australian taxa. Prior to modern legislation, several species were driven to extinction by hunting (e.g. Lord Howe swamphen (*Porphyrio albus*), Tasmanian emu (*Dromaius novaehollandiae diemenensis*), Lord Howe parakeet (*Cyanoramphus subflavescens*): Garnett *et al.* 2011). Timber harvesting continues to push species such as Leadbeater's possum (*Gymnobelideus leadbeateri*) (Woinarski *et al.* 2014) and swift parrot (*Lathamus discolor*) (Garnett *et al.* 2011) towards extinction.

Although there are marked contrasts between Australia and the global situation in the rankings of threats, Australia's threat rankings are broadly similar to those of islands worldwide, for which invasive species have been by far the main driver of extinction (Tershy *et al.* 2015; Woinarski *et al.* 2015; Doherty *et al.* 2016).

Australia's responses to threats affecting its threatened taxa

There has been an ongoing response to addressing the threats to Australia's threatened taxa for decades (Stephens and Maxwell 1996). Many government departments, non-government organisations, communities and individuals make significant efforts at local, regional and national scales towards reducing the threats that are causing the decline of these taxa (NRMMC 2010). These efforts include, but are not limited to: establishing and managing the national protected area estate, including Indigenous Protected Areas and private protected areas (NRMMC 2009); active management of threats (e.g. rabbits: Pedler *et al.* 2016) and threatened species (Kangaroo Island glossy black-cockatoo (*Calyptorhynchus lathami halmaturinus*): Berris *et al.* 2018); establishment and maintenance of captive breeding programs (e.g. orange-bellied parrot (*Neophema chrysogaster*): Smales *et al.* 2000); advocating for threatened species protection (e.g. Leadbeater's possum: Lindenmayer and Possingham 2013); collecting data and information to understand species' persistence needs (e.g. palm cockatoos (*Probosciger aterrimus*): Murphy *et al.* 2003); and improving approaches to help guide decision making for improving species survival (e.g. McCarthy *et al.* 2008).

The nation's protected area network forms the cornerstone of these efforts by protecting species habitat (NRMMC 2009), as these areas are the most effective means of mitigating many of the threats that cause habitat loss (Geldmann *et al.* 2013). In Australia, protected areas are vital to counter the numerous and cumulative impact of such threats (e.g. urban development, agriculture, transportation and mining). However, despite recent expansion, many threatened species are afforded little to no protection within Australia's protected area network (Watson *et al.* 2011), much of which is biased towards the continent's arid and infertile interior (Venter *et al.* 2018). Additionally, key threats to Australian threatened species, such as invasive species and fire, often operate irrespective of land tenure (Woinarski *et al.* 2011, 2013; Legge *et al.* 2017) and have contributed to the decline in many populations of threatened species in protected areas across the continent (Wayne *et al.* 2017). Threats such as these, when unmanaged, can transform ecosystems and degrade otherwise intact habitat (Russell-Smith *et al.* 2007; Preece *et al.* 2010). To be effective, protected areas need active management – which requires committed funding – if they are to achieve their goal of protecting threatened species (Kearney *et al.* 2018).

Taxa listed as threatened under the EPBC Act are also afforded legal protection through this primary piece of environmental legislation. The EPBC Act provides a legal framework to protect matters of national environmental significance, which includes threatened taxa, threatened ecological communities, and heritage places (Commonwealth of Australia 2017*a*). The EPBC Act plays a major role in the response to many of the threats affecting Australian threatened taxa, with two main pathways of doing so. First, the EPBC Act's taxon-focussed response is through the preparation of conservation advices, and in some cases, of more extensive recovery plans. These recovery plans, which are binding on the Commonwealth Minister for the Environment (EPBC Act Section 34D(1)(c)), and conservation advices, which the Minister needs to 'have regard to' (Section 34D(1)(ca)), aim to inform the action needed to recover each taxon. As of November 2017, the Australian Government provided details on recovery plans made or adopted under the EPBC Act for 735 threatened taxa and listed 124 taxa for which recovery plans are required to be prepared (Commonwealth of Australia 2013; Commonwealth of Australia 2017*b*). Second, key threatening processes can also be listed under the EPBC Act, and such listing is a first step towards supporting and coordinating efforts to ameliorate its impacts (Hawke 2009). Listing may be followed by the development of a threat abatement plan or threat abatement advice, which provide information on the

research and management actions needed to reduce the impact of threatening processes on listed taxa (Commonwealth of Australia 2016).

Despite the protected area estate, on-ground management and legislative protection, Australia has been unable to reverse or prevent further decline in all but a small minority of threatened species (Garnett *et al.* 2011, 2018; Woinarski *et al.* 2014), and the general trend for threatened taxa is for ongoing decline. Key to this trend is the fact that the impacts of many threats continue to increase. The recent Australian State of the Environment Biodiversity Report highlights an increase in the impact of several key threats to Australian biodiversity, such as the effects of climate change, clearing and fragmentation, livestock grazing, invasive species and pathogens, altered fire and hydrological regimes (Cresswell and Murphy 2017). Cresswell and Murphy (2017) also identify that while progress is being made in management of some threats, resources for the management of many threats are currently insufficient and, in many cases, have declined in recent years. These resource inadequacies have also been identified in both national and international studies of funding for the conservation of Australian biodiversity (McCarthy *et al.* 2008; Waldron *et al.* 2013).

Additional to increasing impact of threats and decreasing resources to manage them, several other impediments to achieving positive outcomes for threatened species have been identified. These include: the ineffectiveness of many threatened species recovery plans, either because they are not funded, or not successfully implemented (Bottrill *et al.* 2011); a loose or unspecified relationship between monitoring results and triggers for emergency conservation actions (Lindenmayer *et al.* 2013); a lack of national, coordinated monitoring and reporting on how well management is working for threatened species recovery (Legge *et al.* 2018); the absence of a comprehensive national plan to recover Australian threatened species (McDonald *et al.* 2015); and the lack of commitment for species recovery (Woinarski *et al.* 2017*a*).

In an attempt to redress some of these impediments, the Australian Government recently developed a national Threatened Species Strategy (Commonwealth of Australia 2015*b*). The strategy aims to use science, action and partnerships to promote the recovery of Australian threatened species. The strategy's main initiatives centre around bringing focus to its priority species, enhancing management attention to particular key threats (notably predation by feral cats) and targets for improving recovery practices (Commonwealth of Australia 2015*b*). The Threatened Species Strategy is an important step towards a nationwide, strategic approach for threatened species recovery. However, to date, the strategy focuses principally on 20 mammal, 20 bird and 30 threatened plant species and one key threat, feral cats (Commonwealth of Australia 2015*b*), and it (or any other comparable plan) does not provide a mechanism for canvassing and then implementing the management needs for the persistence of all Australian threatened species. What is missing is a national-level picture on how best to coordinate efforts and resources for managing threats across all of Australia's threatened species. To turn around the trend of ongoing species decline, Australia needs to move beyond enumerating the threats known to impact threatened taxa, to understanding the extent and severity of each threat, the interactions between them and, importantly, identifying and implementing effective threat management.

What is needed to redress declines of Australian threatened species?

At present, although significant efforts are in place and these may have forestalled some declines and extinctions, the *status quo* is insufficient to conserve Australia's threatened species. A more comprehensive, adequately funded, coordinated national response would enable a clearer definition of the total set of responses required to redress declines of Australia's threatened species. This would include understanding where threatened species occur, where the threats affecting them operate and which location-based actions and legislative support are required to effectively abate key threats to ensure species recovery. Importantly, some of this information is already available for species that have existing recovery plans and national action plans (e.g. for birds and mammals). However, for most threatened species, such plans are absent, outdated or include critical knowledge gaps in species' occurrences, threats and effective recovery strategies. Some of this knowledge is likely held by local land managers, but has not been brought together to enable a clear national pathway to threatened species recovery success.

Below we expand upon five ways to meet this challenge. These are focussed around two broad themes: (1) ensuring financial and legislative support for implementing urgent actions to recover threatened species, including (1a) adequate resources for the implementation of recovery actions, and (1b) effective policy support for response mechanisms and management; and (2) developing, funding and implementing a coordinated national threatened species response, which involves (2a) identifying and filling knowledge gaps in understanding the distributions of species and threats, the severity and interactions of their impacts on species, (2b) understanding how threatening processes (e.g. clearing, pollutants) are impacting species, so that effective response mechanisms can be designed, and (2c) coordinating information and resources to help policy makers and local land managers enable species recovery, including the ongoing collection and sharing of information to guide effective management.

First and foremost, the actions known to be essential and urgent for threatened species survival require funding. Recovery plans, conservation advices and action plans provide information on the actions needed to prevent extinction, and in many cases to enable the recovery, of many species, but come with no resourcing commitments for the implementation of these actions (Ortega-Argueta 2008). For example, two of the three recently extinct Australian species had recovery plans in place (Christmas Island pipistrelle and Bramble Cay melomys) and the actions needed to prevent their extinctions had been identified; however, no or insufficient funding was made available in time to prevent these extinctions (Martin *et al.* 2012; Woinarski *et al.* 2017*b*). If recovery plans are to be effective, just as if Australia's response to the extinction crisis is to be effective, the commitment of adequate funding to support these plans is urgently needed.

Additional to the urgent need for increased funding, management responses to declines of threatened species require the

support of policy and legislation for implementation. The on-ground threatening processes that cause species decline are increasingly impacted by governance factors (Woinarski *et al.* 2017*a*). For example, protected area downgrading, downsizing and degazettement events have affected one-third of Australia's protected area network since 1997 (Cook *et al.* 2017), with many protected areas also opened up to uses incompatible with biodiversity conservation (Ritchie *et al.* 2013). The loss and degradation of threatened species' habitat has occurred despite current land-clearing laws (Reside *et al.* 2017; Rhodes *et al.* 2017), with several state governments allowing logging in critical species' habitat, including old-growth forests and protected areas (e.g. Lindenmayer and Possingham 2013; Stojanovic *et al.* 2017). We also note that while the assessment for listing species under the EPBC Act is a scientific process, the decision to assess, and the decision to list are susceptible to political influence, which can adversely affect conservation efforts. Without governance and legislative support, and committed political leadership, many efforts to conserve Australia's threatened species will be undermined.

Notably, our focus here has been on listed threatened species. However, we suspect that there are many species (particularly of uncharismatic taxonomic groups) that are equally imperilled that have not yet been formally listed as threatened (Walsh *et al.* 2013). To reduce the rate of biodiversity loss, much more attention needs to be paid to recognising the conservation needs of such species, preferably through an expedited process for their listing.

Beyond these urgent implementation priorities, the development of a more coordinated national response for threatened species recovery would create clearer pathways to achieving longer-term success. This would include identifying and filling critical knowledge gaps, especially for the many species without complete recovery plans as, at present, only 42% of EPBC Act–listed threatened species have had recovery plans prepared (Commonwealth of Australia 2017*b*). Much of this information is dispersed amongst numerous government and non-government agencies, land managers and other experts working across a region, and could be brought together through a coordinated national approach. Additional essential information can be obtained over time through surveys, experimental management and monitoring of species' responses. Bringing this information together would not only improve the coordination of actions, and therefore efficiency, it would also improve the alignment between on-ground efforts and higher-level decision-making to ensure actions are supported by policy.

Improved information on the extent (over how much of the species' range the threat impacts) and severity (rate of decline caused) of the individual and interactive impacts of each relevant threat to threatened species, especially those for which we have data shortfalls, is an important precursor for a coordinated national response to abate the threatened species crisis. At present we are limited in our understanding of where and how threats operate across landscapes (Evans *et al.* 2011), although we do know that impacts vary considerably across different ecosystems (Price *et al.* 2008) and taxa (Clavero *et al.* 2009). Threats operate in a complex environment, interacting with their surrounds and often with other threats (Doherty *et al.* 2015). Some threats have an antagonistic effect on one another (Côté *et al.* 2016), while others have additive and even synergistic effects (Brook *et al.* 2008). Currently, there is extensive knowledge on some threats (e.g. cats: Legge *et al.* 2017; Woinarski *et al.* 2017*b*), some interactions (e.g. fire and climate change: Bradstock *et al.* 2014; fire and introduced predators: McGregor *et al.* 2014), and their impacts on some threatened species (e.g. birds: Garnett *et al.* 2011; mammals: Woinarski *et al.* 2014). However, a comprehensive understanding of the threats, their interactions and the severity of their impacts to all EPBC Act–listed species is lacking.

An improved understanding of how threats are causing species declines is also required, to enable the development of response actions. The IUCN threat classification scheme used here includes many threats that are entangled and key processes of interest are dispersed across several categories. In particular, habitat loss, fragmentation and degradation are disaggregated into the IUCN threat categories of urban development, human disturbance, energy production, transportation, and some components of ecosystem modifications and agriculture. This disaggregation has contributed to confusion about the relative importance of habitat loss, fragmentation and degradation for threatened species (e.g. Wintle and Bekessy 2017; Booth 2018); however, this process is recognised as a leading cause of species decline and extinction in Australia (State of the Environment Committee 2011; Cresswell and Murphy 2017). An understanding of how threats result in particular species declines in which places is needed to enable the development of suitable response mechanisms, whether these are related to policy, planning or on-ground management actions. Estimating the costs and likely benefits of these actions will enable an understanding of the resources required to implement various actions as part of a national response.

Finally, threatened species recovery in Australia would benefit from the collation of existing and new information to build, support, implement, and learn from a coordinated national response. A range of governments, non-government organisations, Indigenous rangers and organisations, private industries and philanthropists provide resources and efforts across all types of land tenure in Australia to support threatened species conservation. A national-level understanding of current conservation actions across the continent would provide a much-improved understanding of progress (and current shortfalls) towards achieving outcomes for threatened and declining species (as well as other aspects of biodiversity), and where more support is needed. This could involve collating locally held information on the management needs of species and the actions that are already in place, to help identify gaps. Information systems are already in place that could be adapted to achieve this. For example, the Monitoring, Evaluation, Reporting and Improvement database collates information on federally funded threat and other natural resource management actions across Australia (Commonwealth of Australia 2014). Building upon, or learning from, such a database would provide a more comprehensive knowledge base of threatened species management in Australia. Future management decisions at the ground level, and policy or funding decisions at higher levels could then be based on the best available information on how to complement existing efforts and progress towards meeting international, national and local goals for species conservation.

Conclusion

We found that invasive species, ecosystem modifications (particularly changed fire regimes) and agriculture are the most prevalent threats to Australian threatened taxa. While we note that some progress has been made in response to many of these threats, the ongoing decline of many threatened species indicates that these efforts have not been enough. We emphasise that, while essential, protected areas alone will not effectively combat the impacts of many of these threats, highlighting the need for comprehensive threat management across the continent as well as more effective threat management within reserves. We highlight that if Australia is to conserve its globally significant biodiversity, a better-planned response supported by adequate funding and effective policy and legislation is urgently needed.

Conflicts of interest

The authors declare no conflicts of interest.

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